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Search for anomalous tau production in b-tagged top quark events

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We present a search for the anomalous production of high transverse momentum taus in the decay products of pair-produced top quarks using 335 pb^{-1} of data taken with the CDF detector in Run II at the Tevatron. We select events with a tau, an electron or muon, large missing transverse energy, and jets, in which at least one b quark is identified using a secondary vertex tagging algorithm. We find good agreement between the number of events predicted by the Standard Model and the number observed. In the context of the Minimal Supersymmetric Model, we place an upper limit on the top quark branching fraction to a charged Higgs boson ($H^{\pm}$) and b-quark. We expect to exclude $\mathcal{B}(t \to H^{+} b) > 0.34$ at 95% confidence level for a charged Higgs mass of 120 GeV/c^2.

Preliminary Results for Summer 2006 Conferences

I. INTRODUCTION

Many extensions of the Standard Model (SM) contain new particles that decay preferentially to third-generation leptons and quarks. This note describes the search for anomalous production of tau leptons in the decay products of pair-produced top quarks with the CDF detector at the Fermilab Tevatron. The CDF detector is described in detail in [1]. The event signature consists of a high p_T tau and electron or muon, large missing transverse energy ($\not\!\!E_T$), and greater than or equal to two jets where at least one of the jets is identified using a secondary vertex tagging algorithm. The expected number of events depends only on known SM cross sections and methods for evaluating jets that are misidentified as taus based on the data.

However, the results can be interpreted in the context of the Minimal Supersymmetric Model (MSSM)(*e.g.*, reviewed in Ref. [2]) where the decay $t \rightarrow H^+ b$ competes with the SM decay $t \rightarrow W^+ b$. There have been previous direct searches for the charged Higgs boson at LEP [3] and in top decay at the Tevatron in Run I and Run II in different final states [5], as well as indirect results using $b \rightarrow s\gamma$ decay rates [4]. Most recently, CDF has measured $\mathcal{B}(t \rightarrow H^+ b) < 0.4$ at 95% confidence level for $80 \leq m_{H^\pm} \leq 160\,\mathrm{GeV}/c^2$ assuming $\mathcal{B}(H^+ \rightarrow \tau^+\nu_\tau) = 1$ [6].

II. DATA SAMPLE & EVENT SELECTION

This analysis uses 335 pb^{-1} of data collected from March 2002 to August 2004. Events are first identified in the trigger system by the requirement of at least one central high p_T electron or muon candidate.

Electron candidates are identified as a high-momentum track in the tracking system matched to an electromagnetic cluster reconstructed in the calorimeters with $E_T > 20$ GeV. The ratio of hadronic to electromagnetic energy deposition in the cluster is required to be low to ensure the validity of the electron hypothesis. We also require that energy shared by the towers surrounding the cluster is low. Muon candidates are reconstructed as high-momentum tracks with $p_T > 20$ GeV/c matching hits in the muon chambers. Energy deposited in the calorimeter is required to be consistent with a minimum ionizing particle.

We introduce a new method for reconstructing and selecting taus based on the output of a likelihood discriminant. Taus decay to hadrons (τ_H), and an associated tau neutrino, about 65% of the time. We reconstruct taus as four separate types based on the final state particles in the decay as shown in Table I. The reconstruction first matches well measured tracks to central jets in the calorimeter. We use the direction of the highest p_T track pointing at the jet to define a tau-signal cone, whose opening angle depends on the energy of the jet, and an isolation cone extending from the signal cone opening angle outward to 30 degrees. We add π^0 candidates made from clusters in the Central Electromagnetic Strip Chamber.

Tau Type	No. of tracks	No. of π^0 s	Br. frac. of τ_H
`Type1`	1	0	18%
`Type2`	1	≥ 1	57%
`Type3`	3	≥ 0	24%
`Type4`	2	≥ 0	0%

TABLE I: Definition of the reconstructed tau types used in this analysis according to the number of tracks and π^0 s in the final state and their relative importance based on hadronic tau branching fractions.

We create a likelihood discriminant to distinguish the reconstructed tau candidates from jets (referred to as the `Tau-Jet` likelihood). For N variables characterizing the candidate, the likelihood is defined as

$$\mathcal{L} = \frac{\prod_i^N \mathbf{P}_S^i(x_i)}{\prod_i^N \mathbf{P}_S^i(x_i) + \prod_i^N \mathbf{P}_B^i(x_i)}$$

where $\mathbf{P}_S$ ($\mathbf{P}_B$) is the signal (background) probability for variable i. By construction the likelihood is normalized between $[0, 1]$ with values near one indicating high signal probability. We obtain the signal probabilities using simulated $t\bar{t}$ events containing hadronic tau decays and use candidates from jet-triggered data samples for the background distributions. The variables used to characterize the tau depend on tracking isolation, EM calorimeter isolation, ratios of track p_T and calorimeter E_T, and maximum d_0 significance, which is defined as the maximum track impact parameter with respect to the beamline divided by its error. Some variables are only used to characterize a particular tau type though the majority are used for all types. The shapes of the `Tau-Jet` likelihood output for simulated taus and reconstructed objects in the jet-triggered data are shown in Fig 1. In addition, we apply an explicit electron and

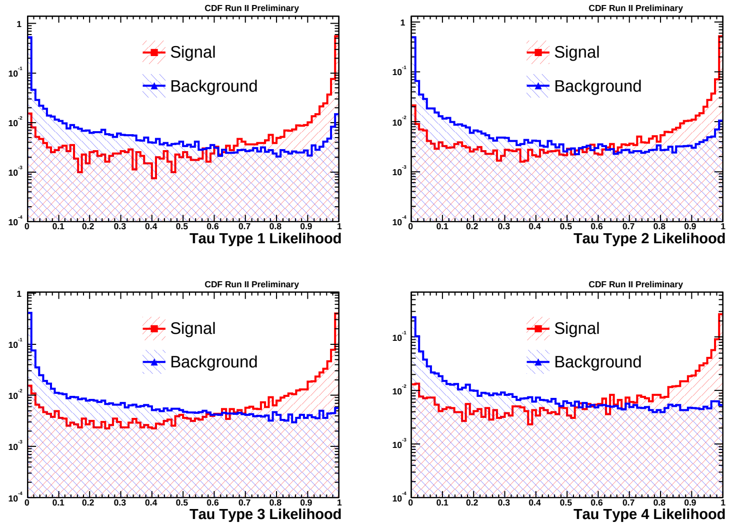

FIG. 1: `Tau-Jet` likelihood shape for `Type1` (upper-left), `Type2` (upper-right), `Type3` (lower-left), and `Type4` (lower-right) candidates using hadronically decaying taus from $t\bar{t}$ decays in the simulation (red hatched histogram) and reconstructed objects in jet-triggered data (blue hatched histogram).

muon veto to tau candidates. We require that the event contain exactly one reconstructed tau with $p_T > 10$ GeV/c and likelihood output > 0.65.

The missing transverse energy is measured by the imbalance in the calorimeter transverse energy and is required to be > 20 GeV. Jets are reconstructed with the JETCLU cone algorithm with a radius $R = \sqrt{\eta^2 + \phi^2} = 0.4$. We require that the event contain at least two jets with the leading jet $E_T > 25$ GeV and the second leading jet $E_T > 15$ GeV. We require that at least one jet with $E_T > 15$ GeV is identified as a b quark candidate through the presence of a displaced vertex within the jet arising from the decay of a long-lived bottom hadron (b-tag). In $t\bar{t}$ events, the SECVTX [7] algorithm is $(48 \pm 4)\%$ efficient for identifying b-quark jets with a corresponding rate of misidentifying light-flavor jets (mistag) of $(1.2 \pm 0.1)\%$.

We use the term H_T to denote the scalar sum of the electron or muon p_T, tau p_T, $\not\!\!E_T$, and E_T of the jets in the event. We require that $H_T > 205$ GeV. For events consistent with a $Z(\tau\tau)$ topology, we require that the invariant mass of the electron or muon, $\not\!\!E_T$, and tau is greater than 120 GeV/c^2.

III. BACKGROUNDS

There are two main types of background in this analysis: events containing a real tau and events containing a jet that is misidentified as a tau. Events with pair produced top quarks where the W from one top quark decays to a tau and the W from the anti-top quark decays to an electron or muon comprise the largest source of the former background. This background is estimated using simulated Pythia [8] top quark events where the acceptance is measured to be $(0.0837 \pm 0.0025(\text{stat}))\%$. There are also smaller backgrounds consisting of a final state with a real tau and electron or muon from WW, WZ, and $Z(\tau\tau)$ decays that are evaluated using the simulation.

All the backgrounds that consist of a misidentified tau are evaluated from the data. Events where a W is produced in association with jets comprise the largest source of this background. We construct a three-dimensional parameterization of the rate that a jet is identified as a tau in jet-triggered data where the contribution from real taus is negligible. The parameterization depends on the p_T, track isolation, and calorimeter isolation of the tau candidate. We use this parameterization to predict the rate of misidentified taus in a sample triggered on multi-jet activity and on a high E_T photon. We find that we are able to predict the number of fake taus to within 20% in the different samples. We also use a parameteriztion derived from jet-triggered data to predict the rate that a light quark jet is misidentified as a b-jet.

IV. SYSTEMATIC UNCERTAINTIES

There are two dominant systematic errors that effect the predicted number of events: the uncertainty in the tau$\to$ jet misidentification rate (20%) and in the difference in the `Tau-Jet` likelihood selection efficiency in the data and the simulation (15%). The former was measured by predicting the number of fake tau candidates in various background samples as mentioned previously. The latter was measured using a large sample of reconstructed $Z(\tau\tau)$ decays in the simulation and data assuming the SM production cross-section. The systematic uncertainty in the b-tag efficiency has been evaluated as 7.5% and the uncertainty associated with the light flavor jets identified as b-jets is 11%. The complete list of systematic errors is summarized in Table II.

Source	Relative Error
jet$\to$ τ misidentification	20%
Tau identification	15%
b-jet identification	7%
jet$\to$ b-jet misidentification	11%
Jet energy scale	5%
Lepton identification	2%

TABLE II: Summary of the relative systematic uncertainties.

V. RESULTS

The expected events from each background source are shown in Table III. We expect about two events from $t\bar{t}$ decay and two events from misidentified jets and observe six events in the data. There is a 20% probability to observe greater than or equal to six events with 3.88 ± 0.52 events expected.

	Electron, Tau	Muon, Tau	All
$t\bar{t} \to \tau$	1.22 ± 0.22	0.85 ± 0.15	2.07 ± 0.37
fake τ,b-jet	0.65 ± 0.14	1.10 ± 0.22	1.74 ± 0.36
Other	0.03 ± 0.03	0.02 ± 0.02	0.06 ± 0.06
Total	1.90 ± 0.26	1.97 ± 0.27	3.88 ± 0.52
Data	4	2	6
Prob.	0.13	0.58	0.20

TABLE III: Summary of expected and observed number of (electron or muon, tau, $\not\!\!E_T$, b-tag) events. The last row represents the probability to observe at least as many events as found in the data given the expected number and its error.

A. Limit

We now set a limit on the number of excess events at 95% confidence limit (CL) according to a Bayesian approach We assume a flat prior for the probability distribution of the non SM signal. We find that the upper limit on excess events is 8.5 at 95% confidence level. We wish to turn this upper limit on the number of excess events into an upper limit on $\mathcal{B}(t \to H^+ b)$ assuming $\mathcal{B}(H^+ \to \tau^+\nu_\tau) = 1$ (as it would be at large tan β (> 3) in the MSSM). Let us denote $\mathcal{B}(t \to H^+ b)$ as x. We write the number of expected events including contributions from $\mathcal{B}(t \to H^+ b)$ as

$$N = \mathcal{L}\sigma(t\bar{t})A^{\ell\tau}_{tot}(x, m_{H^\pm}) \quad (1)$$

where

$$A^{\ell\tau}_{tot} = (1-x)^2 A^{\ell\tau}_{WW} + 2x(1-x)A^{\ell\tau}_{WH} + x^2 A^{\ell\tau}_{HH}$$

and A_{WW}, A_{WH}, and A_{HH} are the respective total acceptances for $t\bar{t}$ pair decays into $W^\pm W^\mp bb$, $W^\pm H^\mp bb$, and $H^\pm H^\mp bb$. We assume the next-to-leading-order SM value for the $t\bar{t}$ production cross section [9] and measure the acceptance terms of the above equation in simulated Pythia events for various generated masses of the charged Higgs

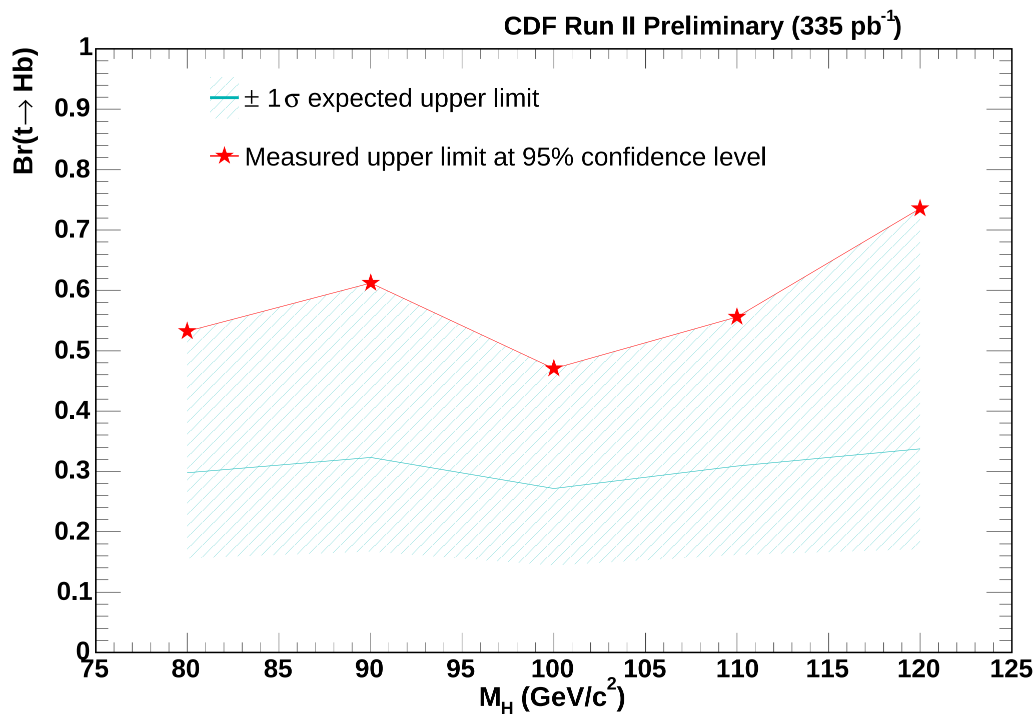

FIG. 2: Measured and $\pm 1\sigma$ expected upper limits on $\mathcal{B}(t \to H^+ b)$ as a function of charged Higgs mass.

between 80 and 120 GeV/c^2. The upper limits that we derive on $\mathcal{B}(t \to H^+ b)$ as a function of charged Higgs mass are shown in Fig 2. We expect to exclude $\mathcal{B}(t \to H^+ b) >\sim 0.30$ at 95% CL mostly independent of charged Higgs masses between 80 and 120 GeV/c^2.

We show how the expected upper limit on $\mathcal{B}(t \to H^+ b)$ scales with integrated luminosity in Fig. 3 assuming that the fractional uncertainty on the number of expected events stays constant. With 1 fb^{-1} of data we expect to measure $\mathcal{B}(t \to H^+ b) < 0.1$ at 95% CL.

B. Event displays

We show a close up view of the inner layer of the Silicon detector for run 177314 and event 2950396 in Fig. 4. This event contains an electron, a tau reconstructed as a track and a π^0 with mass 1.78 GeV/c^2, two b-tagged jets and an additional jet. The r-ϕ and lego views of this event are shown in Fig. 5. Fig. 6 shows the r-ϕ and calorimeter tower lego views for event 186591/2603400 that has an electron, a tau that decays to a single track, 1 b-tagged jet, and two additional jets. Note that the highest E_T jet in the event (one that does not have a SECVTX b-tag) contains a track with a corresponding stub in the muon detector with an impact parameter with respect to the SVX beamline of 2 mm

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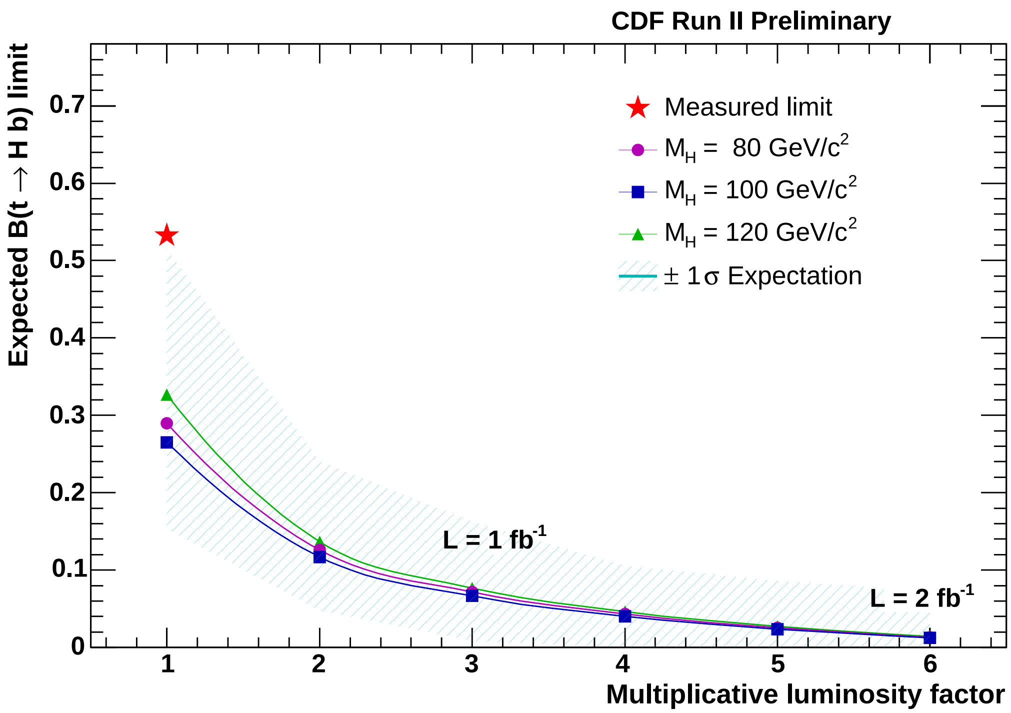

FIG. 3: Expected upper limit at 95% CL on $\mathcal{B}(t \to H^+ b)$ as a function of integrated luminosity for three values of the charged Higgs mass. The $\pm1\sigma$ expected region is for a charged Higgs mass of 80 GeV/c^2. The measured upper limit with 335 pb^{-1} is shown as the red star for an 80 GeV/c^2 Higgs mass. With 1 fb^{-1} we expect to exclude $\mathcal{B}(t \to H^+ b) > 0.1$.

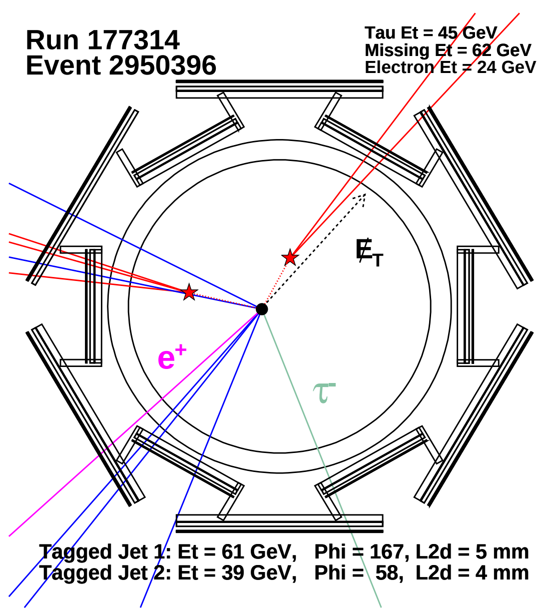

FIG. 4: Event/run 177314/2950396 with two tagged b-jets and a tau with reconstructed mass 1.78 GeV/c^2 that decays to a single track and π^0. The vertices of the tagged jets are indicated as red stars.

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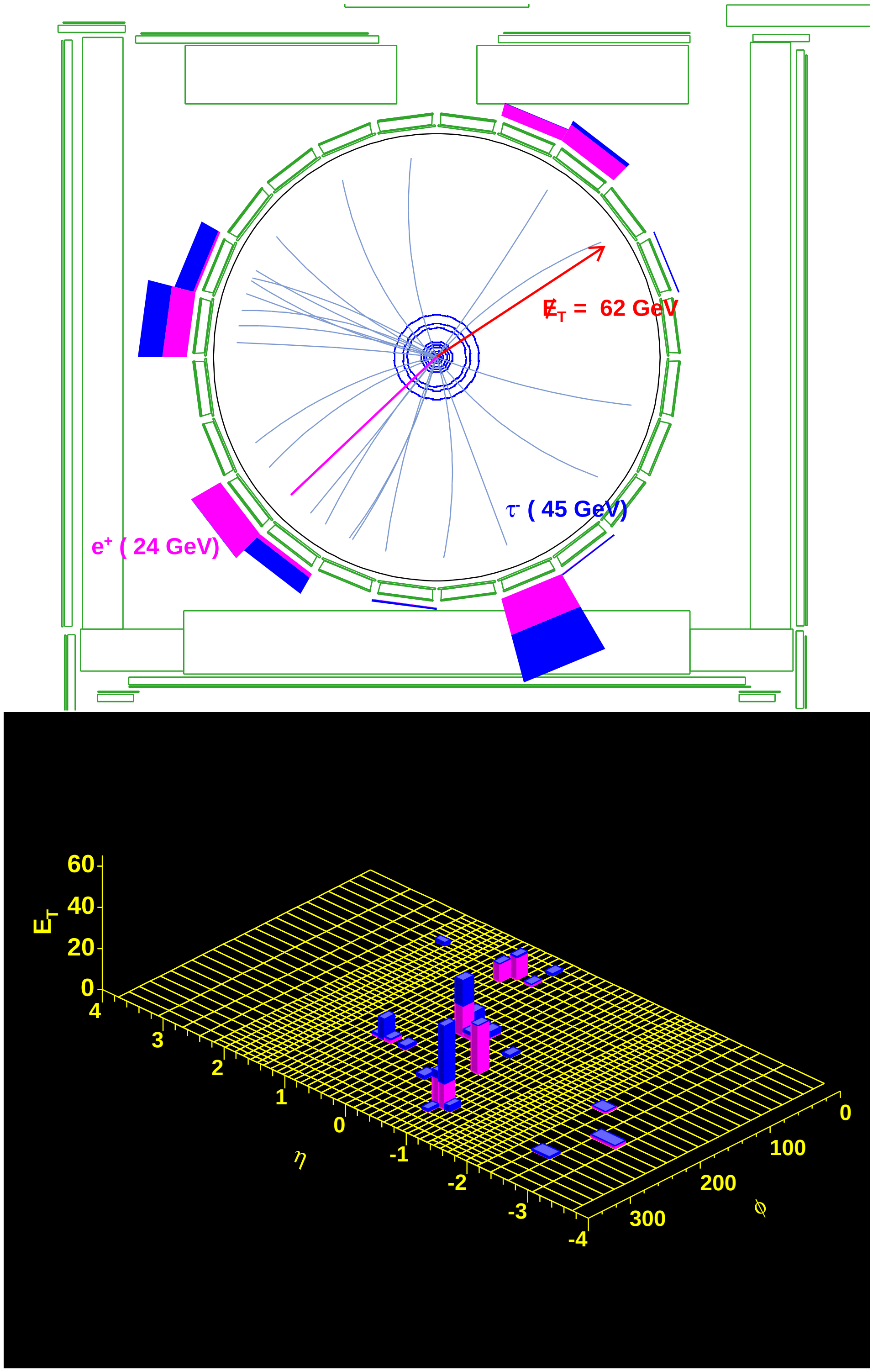

FIG. 5: COT (top) and calorimeter tower lego view (bottom) for the double b-tagged event 177314/2950396. We have required the track p_T and tower E_T to be > 1 GeV/c and > 1 GeV respectively.

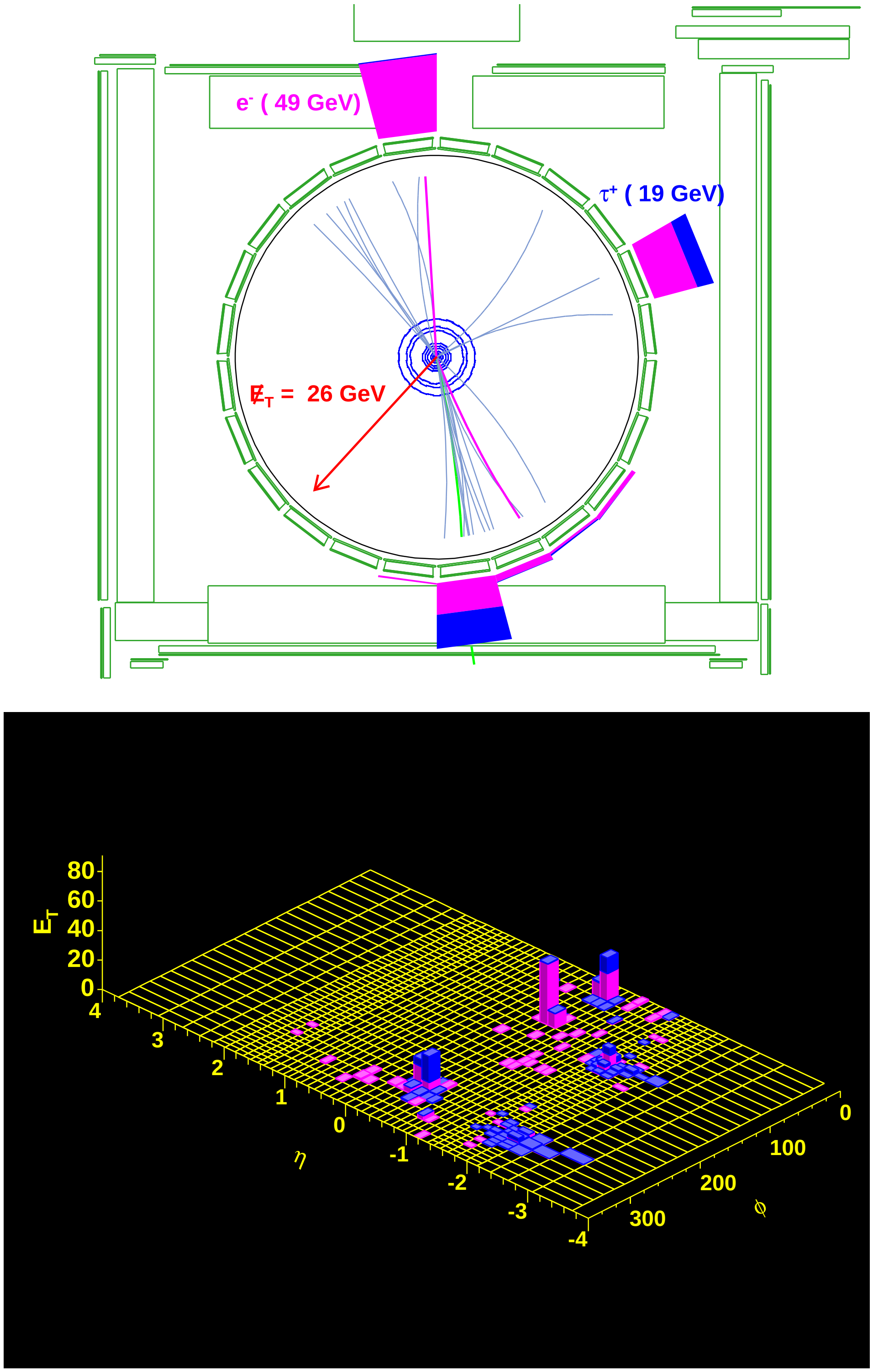

FIG. 6: COT (top) and calorimeter tower lego view (bottom) for the b-tagged (electron,tau) event 186591/2603400. We have required the track p_T and tower E_T to be > 1 GeV/c and > 1 GeV respectively. Note the presence of the muon inside the highest E_T jet (one that does not have a SECVTX tag).

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